Tunnelling and Underground Space Technology 81 (2018) 103–111

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Tunnel lining design in multi-layered grounds

Ngoc-Anh Do[a], Daniel Dias[b,c,*]

[a] Department of Underground and Mining Construction, Faculty of Civil Engineering, Hanoi University of Mining and Geology, Viet Nam
[b] School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei, China
[c] Univ. Grenoble Alpes, CNRS, Grenoble INP, 3SR, F-38000 Grenoble, France

ARTICLE INFO

Keywords:
Finite element method
Tunnel
Lining
Multi-layered ground
Earth pressure

ABSTRACT

Multi-layered grounds are usually encountered during tunnel excavations. However, tunnel design methods often adopted the homogeneous ground assumption for the sake of simplicity. This paper focuses on improving the performance of the Hyperstatic Reaction Method (HRM), which is part of the numerical method category, in the case of multi-layered grounds. A special attention is paid to the change of the weaker ground layer's position over the cross-section of the tunnel and of the ground layer's thickness. The numerical HRM model was validated based on a comparison with monitoring data from a real site and with those of finite element (FEM) models for different cases of multi-layered grounds. The results indicated that a reduction of the upward pressure applied on the lower half of the tunnel for the HRM model needs to be considered. Using the HRM model, a parametric study was conducted to highlight the significant dependency of the tunnel lining to the position and the thickness of the weaker ground layer.

1. Introduction

The Hyperstatic Reaction Method, which is part of the numerical method category, is particularly appropriate for the design of tunnel support structures (Oreste, 2007; Do, 2014; Do et al., 2014a). As most of the tunnel lining design models, the HRM model was mainly applied in homogeneous grounds (Oreste 2007, Do et al., 2014a, 2014b). However, multi-layered grounds are usually encountered during the excavation of tunnels. The change of the position and of the thickness of ground layers on the cross-section of the tunnel can, therefore, be observed. Consequently, the ground pressure acting on the tunnel lining and the interaction between the tunnel lining and the surrounding ground could be significantly modified due to their dependency to the properties, thickness and position of the ground layers. Many researchers also paid attention to this configuration of multi-layered formation by using experimental models (Nunes, 2008; Berthoz, 2012; Zhang et al., 2015) and numerical models (Jenck et al. 2004; Nunes, 2008; Katebi et al., 2015; Zhang et al., 2015; Ibrahim et al., 2015). Jenck et al. (2004); Berthoz (2012); Ibrahim et al. (2015) took into consideration the effect of the soil stratification on the tunnel face stability. Nunes (2008) presented a combination of experimental and numerical analysis. The objective of this study was to estimate the soil-tunnel interaction within a tunnel excavated in a multi-layered ground. The presence of the sandy stratum located over the tunnel crown had a significant effect on the response of the tunnel. However, the whole tunnel cross section was excavated in a sandy soil layer. Katebi et al. (2015) studied the effects of the ground stratification on tunnel lining loads. Significant differences on tunnel lining forces obtained in three cases (two-layers including sand overlying by silty soil, a homogeneous silty soil and a homogeneous sandy soil model) were observed. Zhang et al. (2015) considered the tunnel lining behaviour in terms of structural forces depending on the relative layer's thickness. They used a combination of physical models and FEM models. The results indicated that on multi-layered grounds, a linear increase of the relative granular layer thickness compared to the tunnel diameter could reduce non-linearly the magnitude of both the bending moments and the movements. The distribution of the bending moment and of the movements along the tunnel perimeter were found to be strongly dependent on the relative stiffness of the layered grounds. Unfortunately, the influence of the layer position over the tunnel height was not mentioned. The above literature review showed the considerable influence of the ground stratification parameters on the tunnel lining response. However, the effect of the ground layer's thickness and of its position on the tunnel cross-section was not clearly addressed. The first goal of this study is, therefore, to improve the performance of the HRM model in the case of multi-layered grounds. Special attention is paid to the change of the weaker ground layer's position over the tunnel cross-section and of its thickness.

* Corresponding author at: School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei, China.
E-mail address: d.dias69@gmail.com (D. Dias).

https://doi.org/10.1016/j.tust.2018.07.005
Received 26 April 2017; Received in revised form 6 June 2018; Accepted 7 July 2018

In addition, the use of the HRM model requires the evaluation of the ground active loads applied to the support structure. However, the ground pressure acting on the tunnel lining is up to now one of the major issues to be addressed in tunnel design due to the uncertainty of the ground distribution surrounding tunnels and to the interaction between the tunnel lining and ground (Takano, 2000; Han et al. 2017). The ground pressure acting on the tunnel lining can be calculated using many existing methods which may be divided into four groups: empirical and semi-empirical methods, ring and plate models, ring and spring models, and numerical models (Kim and Eisenstein, 2006). Most of these methods have been reviewed in detail by many authors (Duddeck and Erdmann, 1985; Kim and Eisenstein, 1998; Takano, 2000) and will therefore not be mentioned here again. Ground pressure acting on the tunnel lining can be considered comprising two elements, the vertical and horizontal pressures. The horizontal pressure is usually derived from the vertical pressure multiplied by the lateral earth pressure coefficient. It is therefore important to evaluate the vertical pressures. Considering the presence of reaction elastic springs along the tunnel lining and springs models, Duddeck and Erdmann (1985); Takano (2000) and Oreste (2007) adopted ground pressure models excluding upward vertical pressure at the lower part of the tunnel. On the other hand, on the basis of comparison with Einstein & Schwartz's analytical method (1979) and numerical results using a finite difference program FLAC^{3D}, the active upward pressure at the lower part of the tunnel was considered in studies conducted by Do et al. (2014a, 2014b). The presence of active upward pressures at the lower part of the tunnel was also adopted in Beam-spring model by Mashimo and Ishimura (2003). It is not similar to the pressure models mentioned above, Blom (2002) argued that the upward ground pressure at the lower part of the tunnel must consider the 'weight' of the tunnel, but there is no ground within the tunnel. It is mostly assumed that the dead weight of the tunnel lining itself has an insignificant effect and can be ignored. The upward ground pressures are therefore reduced at the lower half of the tunnel lining. Terzaghi (1941) emphasized that the upward bottom pressure should be essentially the counterpart of the roof pressure, i.e. reaction acting on the lower part of the tunnel. A certain part of this pressure is, however, carried by the surrounding ground. The upward bottom pressure was, therefore, usually found to be smaller than the roof one (Terzaghi, 1941). Obviously, there are uncertainties in evaluating ground pressures acting on the tunnel lining, and particularly for the upward bottom pressures. The second goal of this study is, therefore, to estimate the reduction of the ground pressure at the lower part of the tunnel to be applied in the HRM model.

In this study, an improvement of the HRM model is introduced which allows considering the change of soil properties from point to point along the tunnel boundary. This permits to consider a multi-layered ground medium. The numerical HRM model was validated based on the comparison with monitoring data from the North Bank of the Second Heinenoord tunnel (Bakker et al., 2000) and with those of FEM models for different multi-layered ground cases. The results indicated that a reduction of the upward pressure applied to the lower part of the tunnel needs to be taken into consideration. Using the HRM model in multi-layered soils, a parametric study was conducted to highlight the effect of the position and of the thickness of the ground layers on the tunnel lining structural forces. Generally, when the tunnel is excavated in a multi-layered granular ground, a thickness increase of the weaker intermediate layer leads to smaller maximum bending moments and to higher normal forces in the tunnel lining. In addition, a lower position of the weaker intermediate layer results in a more stable state of the tunnel lining in terms of structural forces.

2. The Hyperstatic reaction method for tunnel lining design

In the HRM method, the tunnel lining is represented by mono-dimensional elements that are able to estimate bending moments, axial forces and shear forces. The ground interacts with the tunnel lining in two ways: through normal and tangential springs connected to the nodes of the structure and through applied active loads. The unknown parameters of the problem are the displacement components of the nodes of the discretized structure. Once these unknown displacements are determined, it is possible to obtain the stresses inside each element and therefore also along the entire support structure. The evaluation of the unknown displacements is made through the definition of the global stiffness matrix of the entire structure and of its connections to the surrounding ground. The global stiffness matrix is obtained by assembling the local stiffness matrices of every single element. On the basis of the estimated nodal displacements, it is thus possible to evaluate the stresses at the nodes of the structure (Huebner et al. 2001).

Details of the numerical HRM approach applied to homogeneous ground soils were introduced in the work of Oreste (2007) and Do et al. (2014a). The fundamental of the new HRM method applied in multi-layered grounds is based on these HRM models. Some significant modifications were proposed to consider the change in properties of different ground layers over the tunnel height, focusing on (1) the active ground pressures on the tunnel lining; (2) the interaction between the different ground layers and the tunnel lining.

2.1. The active pressures

Tunnels can be divided into deep and shallow tunnels, which are significantly different from each other, in terms of disturbance caused by their excavation process on the surrounding ground and, therefore, on the ground pressures acting on the tunnel lining. In deep tunnels, when the overburden thickness is two times larger than the external diameter D of the tunnel lining, the active vertical load σ_v can be estimated using Terzaghi's formula (Takano, 2000). An effective overburden thickness h_0 ($h_0 \geq 2D$) should be used and is determined by means of the following formula:

$$h_0 = \frac{B_1(1-(c/B_1\gamma))}{K_0 \tan\varphi}(1-e^{-K_0 \tan\varphi(H/B_1)}) + \frac{P_0}{\gamma}(e^{-K_0 \tan\varphi(H/B_1)}) \quad (1)$$

$$B_1 = R_0 \cot\left(\frac{(\pi/4)+(\varphi/2)}{2}\right) \quad (2)$$

where c, ϕ and γ are the cohesion, internal friction angle and unit weight of the ground, respectively; K_0 is the lateral earth pressure coefficient and H is the overburden to the tunnel top, P_0 is the overload on the ground surface, R_0 is the external radius of tunnel lining. For multi-layered formations, the average parameter values with a weighting factor of the layer thickness will be used in Eqs. (1) and (2).

In the case of shallow tunnels excavated in multi-layered grounds, when the overburden is twice less than the tunnel diameter, the active vertical load $\sigma_{v(i)}$ at the node i of the tunnel lining in the HRM model can be estimated considering the change in depth over the tunnel height:

$$\sigma_{v(i)} = \sum_{j=1}^{n-1}\gamma_j h_j + \left(z_i - \sum_{j=1}^{n-1} h_j\right)\gamma_n \quad (3)$$

where j is the number of the ground layer countered from the top layer at the ground surface;

n is the number of the ground layer at which the vertical pressure is estimated;
z_i is the depth from the ground surface to the ground pressure level calculation (node i of the tunnel lining in HRM model) (m);
γ_j and γ_n are the unit weights of ground layers number j and n, respectively (MN/m^3);
h_j is the thickness of ground layer number j (m).

The horizontal pressure acting on the tunnel lining $\sigma_{h(i)}$ at the node i of the tunnel lining in HRM model is given by: